Hygrothermal Performance of Flat Roofs with Construction Moisture

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ABSTRACT

Rainwater intrusion in a flat roof during construction is not uncommon and can adversely affect the performance and the durability of the assembly. In order to study the conditions in a flat roof with construction moisture, a new roof was installed on a building close to the meteorological station of a field test site in the alpine region of Germany. The glass wool insulation of the assembly is sandwiched between an aluminum vapor barrier at the inside and an impermeable dark-colored roofing membrane at the outside. During construction, temperature and humidity sensors as well as moisture pins were installed at different positions vertically and horizontally, and approximately 2 L/m^2 of water was added before the roof was sealed from above. The variants investigated include different insulation thicknesses and surface colors as well as test sections shaded by tilted PV elements.

The data collected by the temperature and humidity sensors in the roofs were evaluated and compared to the results of hygrothermal simulations using the simultaneously recorded meteorological data, including long-wave radiation to the sky, as boundary conditions. The dark-colored roof sections show the largest temperature and humidity fluctuations, including comparatively high heat fluxes during summer due to conduction and latent heat effects. In the white roof section, which remains much cooler than the dark one, the moisture stays beneath the roofing membrane and the latent heat effects are comparatively small. Compared to the white roof, the surface temperature of the dark-colored section is lower during daytime and higher at night.

INTRODUCTION

Due to solar radiation and nighttime sky radiation, flat roofs with dark roofing membranes experience higher thermal loads than other building components. Therefore, this construction type was chosen to investigate hygrothermal conditions in glass fiber insulations and the effects caused by latent heat. To increase the moisture content, two liters of water per square meter were inserted into the test roof on the field test site of the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen before closing the construction. The measured conditions in the roof serve to validate hygrothermal simulations. In a second step the influence of latent heat transfer on the total thermal transmittance of the roof was examined using a hygrothermal simulation tool. This was done because Hedlin (1988) as well as Pederson and Courville (1991) have shown that the latent heat effect in wet roofs can seriously impair the thermal performance of the insulation.

This paper presents the experimental investigations carried out on a flat roof under German climate conditions. Continuous measurements of temperature and humidity within the roof assembly are shown, as is the influence of shading by solar panels to the surface temperature compared to a white roof surface. Then, the results obtained by hygrothermal simulations are validated by comparison with these measurements. Lastly, calculations are performed to determine the influence of latent heat effects in the glass wool. Especially for dark roof surfaces, the latent heat transfer in the construction is quite high, which is reflected in the heat transfer on the interior side of the construction.

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INVESTIGATIONS

Field Tests

The subjects of this study are the measured and simulated hygrothermal conditions in an insulated flat roof with the following composition from the exterior to the interior:

- Impermeable roofing membrane (elastomer bitumen, $s_d > 100$ m)
- Insulation layer: 90 mm and 175 mm glass fiber boards, density $\rho = 75$ kg/m^3; thermal conductivity 0.037 W/(mK)
- Vapor barrier (aluminum foil, $s_d > 1500$ m)
- Load-bearing wooden sheathing

Photographs of the test roof in Holzkirchen and a schematic drawing of the roof assembly with the sensor positions are shown in Figure 1. The temperature measurements are performed using PT100 temperature sensors; for the relative humidity, capacitive sensors are used. Prior to the installation, all sensors were calibrated in the laboratory. Before closing the roof surface, approximately 2 L/m^2 of water was introduced into the insulation by spray-wetting. All edges were carefully sealed to avoid any lateral dry-out of the initial moisture. The roof was set up at the field test site of the Fraunhofer IBP in Holzkirchen (South Germany) in August 2006.

After a test period of about two years, one test section of the roof, which originally had a shortwave absorptivity of 0.9, was painted with a white color (measured shortwave absorptivity $a = 0.2$; the factor can increase to 0.3 with time by ageing and the effect of dust). On another test section a solar panel was installed on the dark-colored roof and equipped with additional sensors to measure the temperature in the shaded area compared to the non-shaded area. Again PT 100 temperature sensors are used. The test setup of the solar panel is shown in Figure 2, the white-painted area in Figure 3.

Hygrothermal Simulations

The hygrothermal simulations are performed by applying WUFI® (Künzel 1995; IBP 2008), which allows the transient calculation of coupled heat and moisture transport in building components under real climate conditions. The model has already been experimentally validated by comparison with numerous field tests. For the glass wool, a moisture retention curve based on the research by Peuhkuri et al. (2005) was used and adapted to fit the measured results. The other material parameters are taken from the program's database.

The calculations comparing simulations with field testing spanned a period of six months. The outdoor conditions used were those measured during the test period and include solar radiation and longwave sky radiation from the atmosphere. For indoor climate, the recorded temperature and relative humidity in the attic space beneath the low-sloped roof were used. The 2 L/m^2 of water inserted over the insulation layer figured as the initial condition.

The calculations to assess the importance of latent heat effects were performed with the same software. For outdoor climate, measured data from the test period in 2008 at the field test site in Holzkirchen were used. For the interior conditions, the recommendations from WTA-Guideline 6-2-01/E 2004 (WTA 2004) for indoor climate with normal moisture loads were used (sinusoidal functions of temperature and relative humidity ranging from 20°C/40% in winter to 22°C/60% in summer). The calculations were performed over a time period of one year starting from an initial moisture content of the glass wool layer of 20 kg/m^3. The shortwave absorptivity for the red-brown roofing felt was set to $a = 0.9$ and for the white surface to $a = 0.2$. For the calculations of the influence of latent heat transfer in the glass wool, the construction was simulated with and without latent heat effects (evaporation and condensation of water). It should be noted that a simulation disregarding latent heat effects does not represent reality. However, the

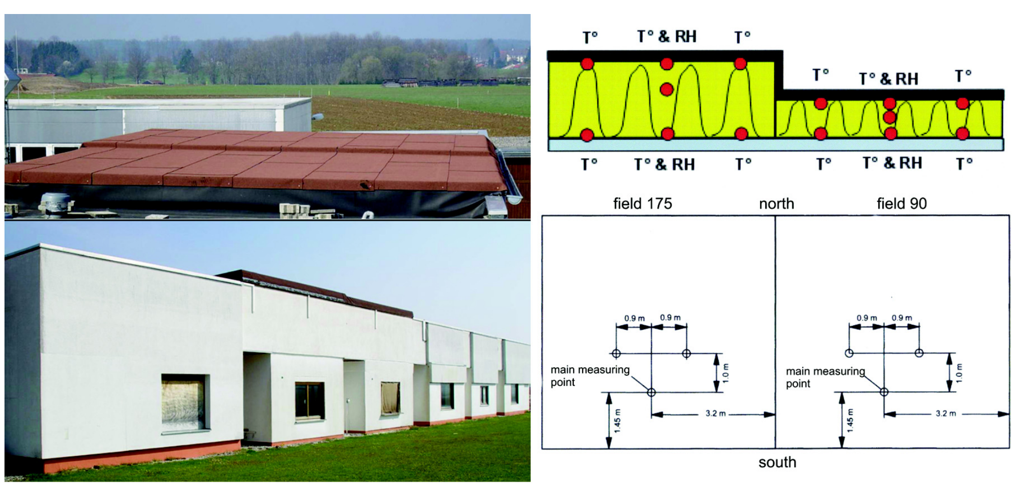

Figure 1 *The test roof (left) and side and top views of the sensor positions (right).*

Figure 2 *The solar panel and the sensor positions.*

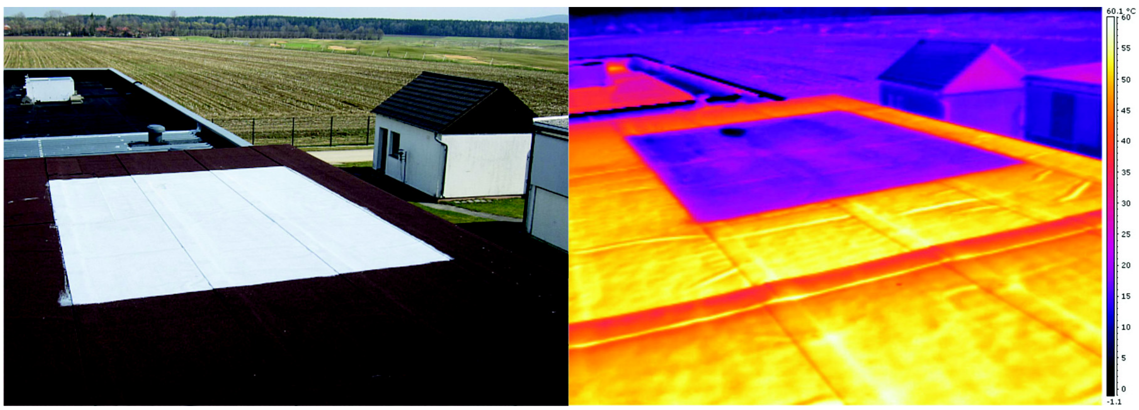

Figure 3 *Photograph and infrared thermograph of the white-painted roof section.*

results come close to those of a dry roof where no moisture redistribution by vapor diffusion happens. Here this calculation is only performed to assess the magnitude of the latent heat effect compared to the total energy flux.

In this paper only the simulation results for the roof with 90 mm insulation are presented because a stronger temperature gradient results in more pronounced latent heat effects. The calculations are performed with the construction assembly modeled according to the drawings in Figure 1.

RESULTS

Field Tests

During and after modifying the test roof by applying a white paint coat and installing a solar panel, the temperature measurements were continued (2008 to 2010). Figure 4 shows measured surface temperatures compared with the ambient air temperature, the solar radiation, and the atmospheric longwave radiation. The bituminous roofing membrane (brownish color) reaches the highest temperatures, about 70°C. With its high shortwave absorptivity of 0.9, most of the radiant energy is converted to heat. The white surface clearly shows lower temperatures on days with high solar radiation about 40°C.

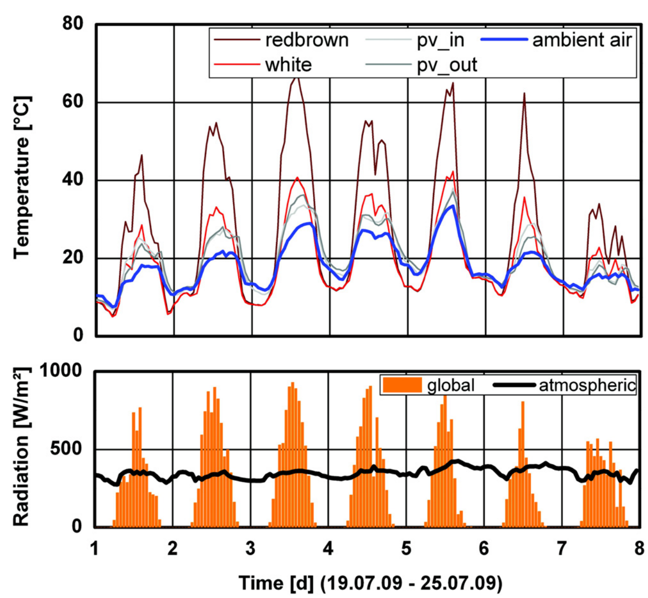

Figure 4 *Measured roof surface temperatures compared with radiation and ambient air temperature during one week in July.*

During the daytime, the white surface gets about 10 K warmer than the ambient air. During the nighttime, both surfaces cool below the temperature of the ambient air. This is due to the longwave emission to the clear sky. This effect is noticeably visible during the second to fourth nights. Both temperature curves of the shaded positions (pv_in and pv_out) show values between those of the white surface and the ambient air during daytime and nearly the same temperature as the ambient air during nighttime. The sensor pv_in is far beneath the panel; pv_out is directed straight under the upper frame of the panel (see also Figure 2). Both positions are never reached by direct solar radiation; they only get a partial amount of diffuse radiation given by the viewfactor to the sky. The longwave emission of the surface decreases by the same factor.

Table 1 shows the monthly mean values of the ambient air temperature and the roof surface temperature for the non-shaded and shaded areas (here only pv_out) during the summer test months (June 2009 to September 2009). During this period, the maximum mean air temperature (17.8°C) occurred in August. In this month, the other surfaces also show their maximum mean values: dark surface, 25.6°C; white surface, 18.5°C; and the shaded surface, 19.7°C. The mean temperature of the shaded surface is always somewhat higher than the mean value of the white surface. While the white surface is on average still a little warmer (by approximately 1 K) than the ambient air in the hot summer months, it has the tendency to be colder during the rest of the year. Apparently, the solar heat gains of a roof with a white surface are compensated by the longwave radiation to the sky. The ten-year average temperature of a horizontal white surface in Holzkirchen lies 0.5 K below the ambient air temperature recorded during the same period (Künzel and Sedlbauer 2007). When there is water in the roof, the vapor pressure, which is driving diffusion and hence the drying process, is close to the saturation vapor pressure.

Table 1. Mean Values of Temperature, °C

Month	Air	Dark	White	Shaded
June	14.0	21.2	15.5	16.4
July	17.1	24.8	18.1	19.1
August	17.8	25.6	18.5	19.7
September	13.9	19.1	13.8	15.1

Table 2. Saturated Vapor Pressure, Pa

Month	Air	Dark	White	Shaded
June	1656	3781	1969	2015
July	2034	5001	2390	2397
August	2130	5411	2495	2509
September	1647	3284	1779	1840

The monthly mean values of the saturation vapor pressure are derived from the hourly calculated temperature values underneath the roofing membrane. Table 2 shows that the values under the dark roofing membrane can exceed the values in the white roof by a factor of two or more. Thus, the surface temperature of a flat roof determines the drying potential of the whole assembly. Therefore, a bright surface (cool roof) can adversely affect the moisture behavior of the structure, as demonstrated by Bludau et al. (2009).

Comparison of Calculation and Experiment

For the validation in this paper, a time period of six months from August 2006 to January 2007 is analyzed. After inserting the initial moisture, the roof was closed in July 2006). The temperatures during Winter 2006–07 were quite moderate, with little snow. There were only a few days with temperatures below –5°C, while in a normal cold winter the temperatures can drop to –20°C at times. The measured temperature and relative humidity within the construction are shown and discussed in comparison with the calculated results in Figures 5–7. In the diagrams, the three sensor positions located at the centers of the roof sections are labeled from outside to inside as "exterior," "middle," and "interior."

Figure 5 shows the measured (blue curve; sensor beneath the roofing membrane) and calculated (red curve) surface temperature of the roof with the 90 mm insulation layer. The agreement between the two curves is very good—only sometimes the peak values show a small difference of 2 K or 3 K. The comparison with the outdoor air temperature (black curve) shows the strong influence of solar radiation (energy source during the daytime) and sky radiation (energy sink during the nighttime), which is accurately captured by the model for radiation and surface heat exchange in the simulation tool.

Figure 6 shows the relative humidity at the three positions within the insulation layer. The overall agreement between measured and calculated curves is quite acceptable. At the

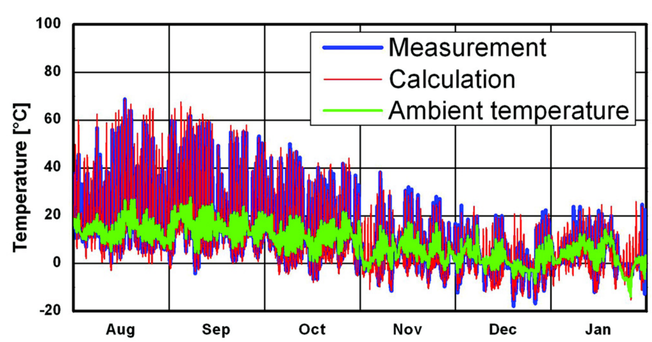

Figure 5 *Comparison of measured and calculated exterior surface temperature variations of the roof with 90 mm insulation and the outdoor air temperature at Holzkirchen.*

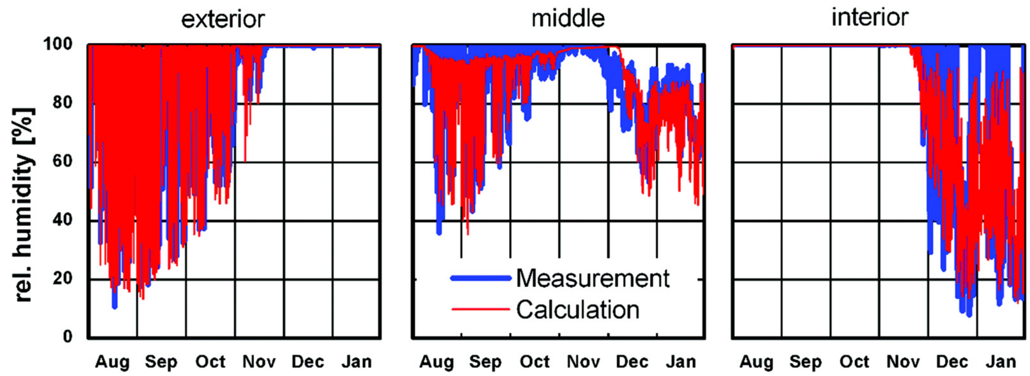

Figure 6 *Comparison of measured and calculated relative humidity variations at the three sensor positions in the roof with 90 mm insulation under the indoor and outdoor climate conditions recorded during the test in Holzkirchen.*

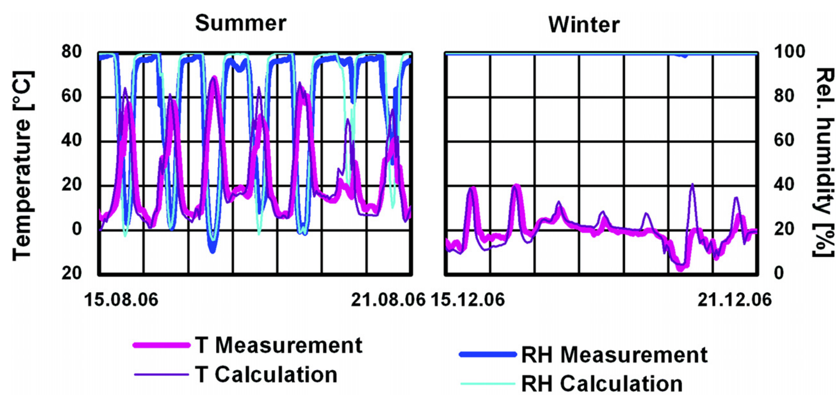

Figure 7 *Comparison of measured and calculated temperature and humidity variations at the exterior sensor position in the roof with 90 mm insulation for two selected weeks in August and December.*

exterior position of the insulation, the calculated and measured curves coincide rather well. This is important since the most extreme temperature and humidity conditions in the insulation layer are observed at the exterior sensor. In summer the relative humidity at this position varies between 20% at noon (when the sun shines and heats up the exterior surface) and 100% during the night. With lower temperatures and shorter days in autumn and winter, the relative humidity at noon increases and remains at 100% from mid-November on. At the middle and interior positions of the insulation layer, the mean shape of the curves is very similar, but the spread of the measured values is slightly larger compared to those of the calculation. This difference may be due to uncertainty concerning the material properties (hysteresis of sorption isotherm) of the glass fiber boards or the assumption of the initial water content in the roof. Also, the measuring error increases with high relative humilities, which also can contribute to the deviation.

A more detailed plot of the hygrothermal conditions for two single weeks in summer and winter at the exterior sensor position (Figure 7) confirms the general good agreement between simulation and experiment. The deviation in surface temperature on December 20 is due to a thin layer of snow on the roofing membrane, which is disregarded in the simulation. An important observation is the opposed variation of temperature and relative humidity beneath the surface of the roofing membrane in the figure. Every time the temperature rises, the measured and calculated relative humidity at the same position drop in an inverse manner. That means high temperature and high relative humidity never coincide at this point.

Influence of Latent Heat Effect

The influence of the latent heat effect in the construction with glass wool is determined by analyzing the heat flux at the interior surface of the roof. In Figure 8, the monthly sums of that heat flux are shown. In the upper diagram the total sums are given; in the lower diagram the total monthly sums are split into total gain and loss, i.e. heat fluxes into the building (positive values) and out of it (negative values). In the diagram, two methods of calculating the heat fluxes are compared: one including latent heat effects and one without (assuming a completely dry roof). In the left diagrams the results for a dark

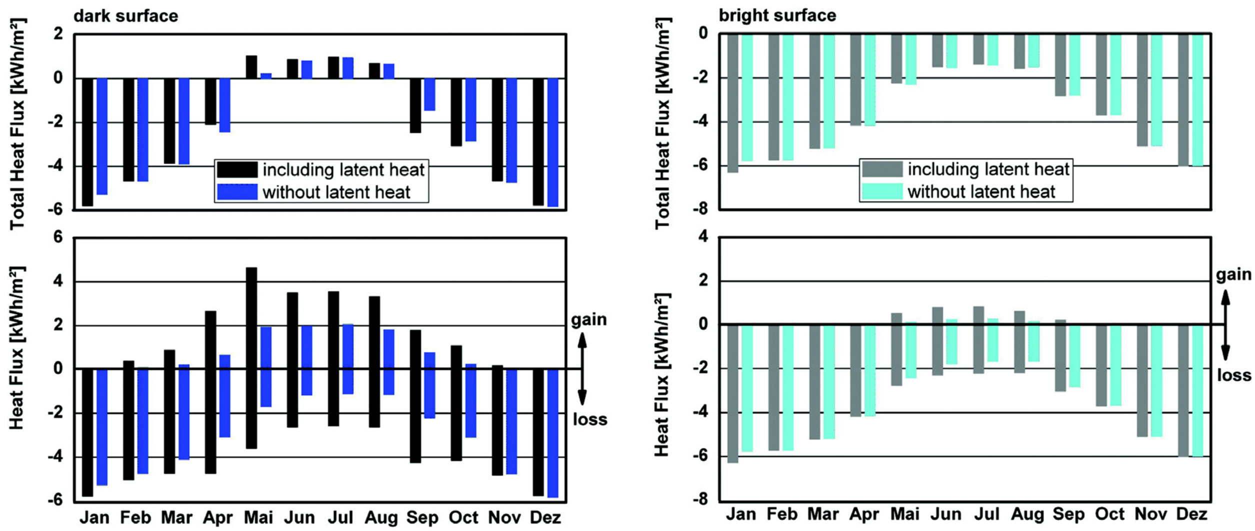

Figure 8 *Sums of monthly heat flux on the interior surface for a dark (left) and a bright (right) roof surface. Upper diagrams show total sum, bottom diagrams show the sums separated in gain and loss.*

surface with a shortwave absorptivity $a = 0.9$ are shown; in the right diagrams the bright surface ($a = 0.2$) is shown.

For the dark surface (left diagrams), the influence of the latent effects during the winter months and swing seasons (January to March and October to December) are small. From April to September, the heat transport by latent effects is about 20% to 50% of the total transport. During this period there are both heat gains and losses caused by the latent effects. The roof with the bright surface (right diagrams) does not show a big difference between both columns—there is hardly any heat transport by latent effects. Total heat gains are very small even in summer.

The hourly values for the heat flux on the interior surface for one day in May are shown in Figure 9. During the nighttime there is an energy loss, while during the daytime, when the sun is shining on the roof, there is an energy gain according to the surface color. The influence of the latent heat is clearly recognizable. In the case of the bright roof, this influence is rather small, while the dark surface shows an important influence of the latent heat effect.

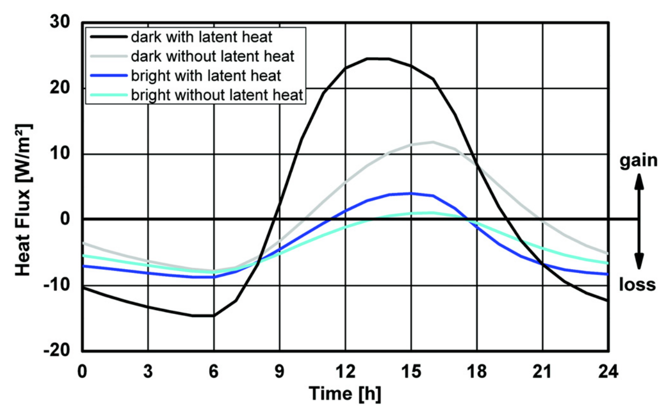

Figure 9 *Hourly values of heat flux for a day in May, calculated with and without latent heat effects.*

CONCLUSIONS

The measurements on the roof with high initial moisture showed that the moisture moves as expected with the temperature gradient from top to bottom during daytime and from bottom to top during nighttime. In winter, all the moisture accumulates beneath the roofing membrane. The calculations showed a quite good agreement with the measurements. That means that the hygrothermal simulation tool is well able to represent the field tests.

Temperature measurements and the corresponding saturated water vapor pressure showed that the temperature and the drying potential are rather low in a construction with a bright or shaded surface. The white surface shows even lower average temperatures and thus also a smaller drying potential than the shaded surface. Using a white surface in the simulation thus represents the worst case also for a shaded roof. Concerning the cooling energy demand in summer, a bright roof surface provides a high savings potential. Compared to the ambient air, the roof surface experiences only slightly higher monthly average temperatures (about 1 K). A dark roof surface gives 5 K to 6 K higher temperatures. But that energy-saving potential of a bright roof surface during summertime is partly offset by a significant reduction in drying potential. In constructions that need to dry to the inside, e.g. wooden lightweight constructions with a low s_d value to the interior, this can cause problems by moisture accumulation, followed by rot.

The simulations also showed a clear influence of the latent heat effects on the total heat fluxes in constructions with vapor-permeable insulation. Especially for roofs with dark surfaces and high temperature differences between the inside and outside, this effect degrades the efficiency of such insulations during summertime. For bright roofs the effect remains small.

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